US Army Corps of Engineers®

Acoustic Nondestructive Testing And Measurement of Tension for Steel Reinforcing Members

Part 2 – Field Testing

by Michael K. McInerney

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) describes the field testing of a nondestructive, acoustics-based technique for measuring tension in steel reinforcing members. Specifically, the technology application addresses the problem of determining tension in concrete-embedded pre- and post-tensioned reinforcement rods.

BACKGROUND: Many reinforced concrete structures contain embedded pre- and post-tensioned steel members that are subject to corrosion and fracturing. Corrosion of steel components can lead to loss of tension and consequent severe problems such as cracking of the concrete or fracturing of the steel. The major problem with existing tension-measurement techniques is that they use indirect, non-quantitative methods to determine whether there has been a loss of tension. We have developed an acoustic technique and transducer to make quantitative tension measurements in a tensioned steel member embedded in concrete.

Acoustic waves are nondestructive. They can travel long distances through engineered structures and can be used to thoroughly interrogate a structure's integrity. Acoustics are dual purpose: they can determine bulk material properties, such as tension, and they can detect small defects, such as fractures. Measurements can be performed very quickly, usually in real time, although post-processing may be required. In this Technical Note, the field testing of a technology application that addresses the problem of determining tension in the concrete-embedded pre- and post-tensioned reinforcement rods used in large Civil Works structures is described. A companion Technical Note, ERDC/CHL CHETN-IX-37 (Part 1–Theory), describes a theoretical basis for bulk tension measurements and an acoustic propagation model.

TENSION MEASUREMENT THEORY: Derivation and development of the acoustic tension-measurement technique is described in detail in Carlyle et al. (2004a, 2004b).

Given equations describing linear elastic deformation and ultrasonic wave speed, an equation describing how to determine tension inside a homogeneous material using pure ultrasonic measurements can be derived. The elastic deformation quantities include Hooke's Law, the Bulk Modulus, Young's Modulus, the Shear Modulus, and Poisson's Ratio. Equation 1 relates tension to the velocities of the longitudinal and shear waves:

$$\sigma = \frac{\mathrm{R}\left(v_{\mathrm{l}}^2 - C\,v_{\mathrm{s}}^2\right)}{C\left(v_{\mathrm{l}}^2 - v_{\mathrm{s}}^2\right)} \tag{1}$$

Tension (σ) is dependent on acoustic longitudinal (v_{l}) and shear (v_{s}) wave velocities, and material properties R and C in Equation 2:

Report Documentation Page

Form Approved OMB No. 0704-0188

1. REPORT DATE **SEP 2014**	2. REPORT TYPE	3. DATES COVERED **00-00-2014 to 00-00-2014**
4. TITLE AND SUBTITLE **Acoustic Nondestructive Testing And Measurement of Tension for Steel Reinforcing Members: Part 2 - Field Testing**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Engineer Research and Development Center,,Vicksburg,,MS**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**11**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

$$C = {}^{c_{11}}\!/\!_{c_{44}} \tag{2}$$

where c_{11} and c_{44} are two of the material's thirty-six stiffness constants.

These equations were derived from the seven fundamental equations shown in Figure 1. These fundamental equations are derived, and the variables defined, in ERDC/CHL CHETN-IX-37 (Part 1–Theory).

Hooke's Law	**Young's Modulus**
$\sigma_{ij} = \lambda\ \delta_{ij}\ \varepsilon_{aa} + 2\ \mu\ \varepsilon_{ij}$	$E = \mu\ (3\ \lambda + 2\ \mu\ ) / (\lambda + \mu\ ) = \sigma_{zz} / \varepsilon_{zz}$
Bulk Modulus	
$K = \lambda + 2\ \mu / 3 = \sigma_{xx} / (3\ \varepsilon_{xx}) = \sigma_{yy} / (3\ \varepsilon_{yy}) = \sigma_{zz} / (3\ \varepsilon_{zz})$	
Shear Modulus	**Poisson's Ratio**
$\sigma_{zx} = 2\ \mu\ \varepsilon_{zx}$	$\nu = \lambda / 2\ (\lambda + \mu\ )$
Longitudinal Wave Speed	**Shear Wave Speed**
$V_l\ = (c_{11} / \rho\ )^{1/2}$	$V_s\ = (c_{44} / \rho\ )^{1/2}$

Figure 1. Fundamental laws and equations governing material properties.

R and C are constants and do not vary with changes in tension. Thus, one needs only to determine, either through measurement or modeling, the velocities of the longitudinal and shear waves.

The acoustic tension-measurement technology described here was awarded a U.S patent in 2009 (McInerney et al. 2009).

FIELD TESTING. Field tests of the acoustic NDT instrument have been completed at three U.S. Army Corps of Engineers dams, one each in Georgia, Oklahoma, and Illinois. Tension measurements were taken on trunnion anchorage anchor rods. Trunnion anchorages are large concrete blocks that anchor the tainter gate trunnions to the dam. (The trunnions are the giant pivots to which the tainter gates are attached.) The concrete anchorages are bolted to the dam with large steel rods that extend through the anchorages into the piers of the dam.

Figure 2 is a photograph of tainter gates and trunnions at one of the test locations. In this picture, the anchor rods are located behind the pairs of vertical rectangular steel enclosures about halfway up from the water line.

The design of these tainter anchorages is shown in Figure 3. It is described in Engineer Manual EM 1110-2-2702. This design was mandated by Headquarters, U.S. Army Corps of Engineers in the 1960s and has been adopted by other government agencies and by industry. It offered advantages over conventional steel beam-and-girder designs, but a significant problem is that the anchor tendons (i.e., rods) are inaccessible for expedient inspection and repair.

A complete post-tensioned anchorage system includes tendons (bars/rods or strands), anchorage devices or bearing plates, ducts, end caps, grout tubes, couplers, anchorage zones, and a corrosion protection system. These components are illustrated in Figure 4.

Figure 2. Typical tainter gates and trunnions.

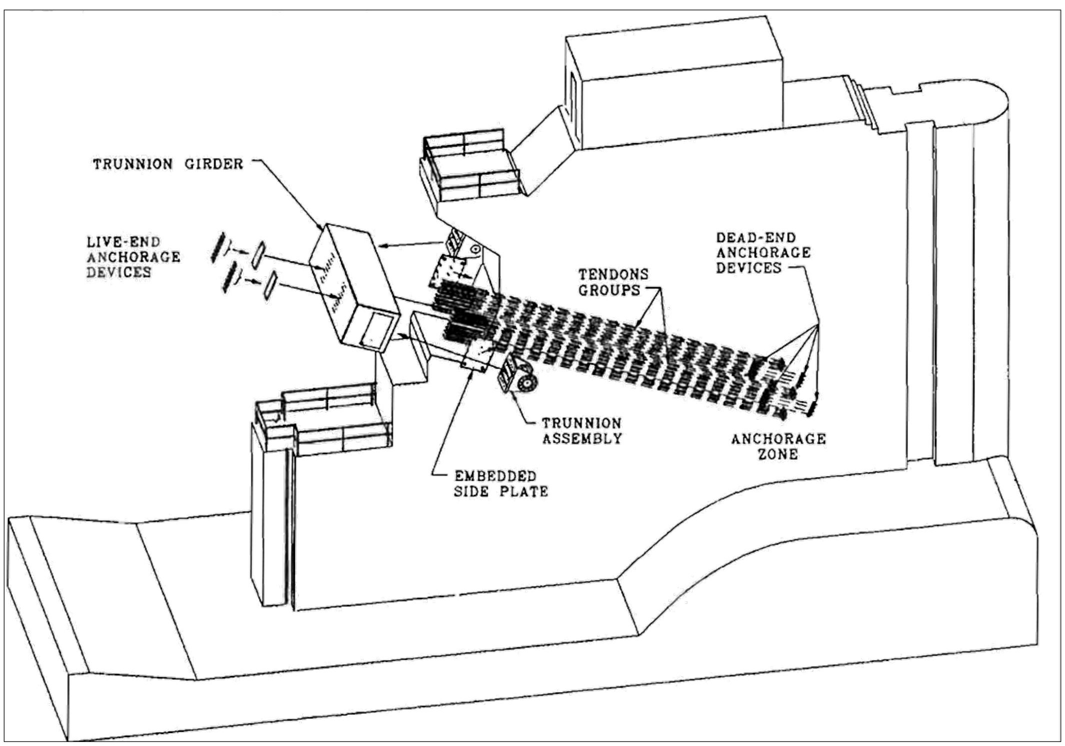


Figure 3. Trunnion anchorage design (from EM 1110-2-2702).

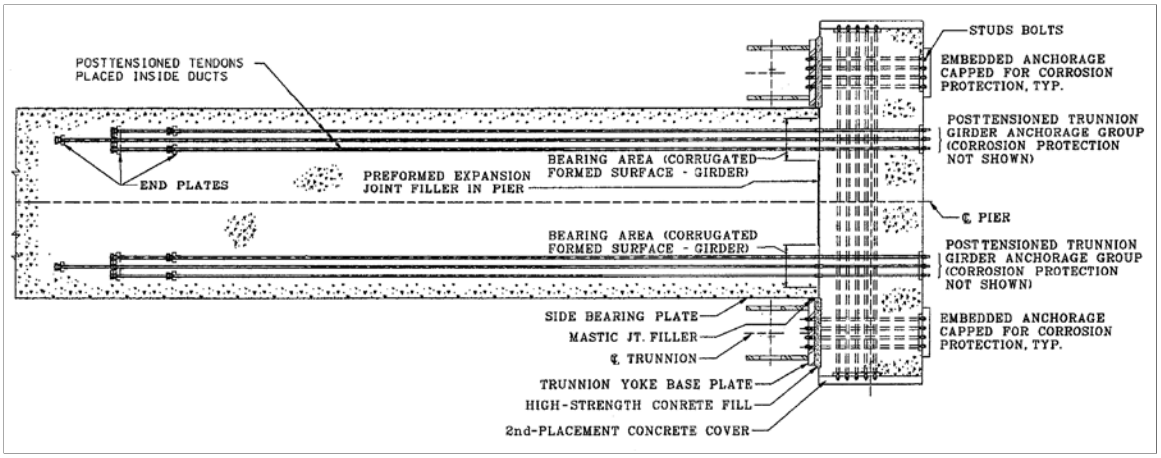


Figure 4. Typical post-tensioned anchorage system (from EM 1110-2-2702).

Ducts encase the tendons to separate them from the surrounding pier and abutment concrete and allow tensioning after the concrete has cured. The ducts also protect anchors during placement of concrete and act as part of the corrosion-prevention system. The tendons are post-tensioned, following installation of the concrete anchorages.

The corrosion-prevention system for tendons consists of tendon ducts, duct fittings, connections between ducts and anchorages, grout tubes, end caps, and filler. The filler material can be either grease or grout. The filler material encapsulates the tendon to prevent corrosion, and is injected after tensioning.

Over the past few years, several tendon (rod) failures have been noted. Figure 5 (left) shows several failed rods—one that has penetrated the cover and two that have dimpled it from the inside upon fracturing. These covers are one barrier to inspecting the rods. They are large and made of heavy gauge steel, and are secured with many bolts or sometimes even peripherally welded to the anchorage. There are no designed inspection hatches, although some have been retrofitted during recent maintenance. As can be seen in Figure 2, these covers are located where access is difficult.

Figure 5. Failed anchor rod penetrating cover, showing one dimple in each cover indicating failed rods that did not penetrate (left); cover removed exposing anchor rods prior to testing (right).

The ends of the rods are visible in Figure 5 (right) where the cover has been removed for anchor rod maintenance and testing.

The first field test was conducted at Keystone Dam in Oklahoma. This dam is an atypical design, as both ends of the rods are exposed. A gallery runs through the dam, providing access to the lower ends of the rods. The rods are also secured with threaded nuts so they can be easily retensioned. Grease is used as filler in the tendon ducts.

Twenty rods (out of 56 total) on a single pier were randomly selected for testing. All rods were 50 ft long. All rod ends were smoothed on the inside of the dam. On the outside, only ten ends were smoothed, leaving ten with rough, flame-cut ends. Consequently, ten rods had good ultrasonic reflectors on the far end (testing was done from the inside) and ten with poor far-end ultrasonic reflectors. Testing showed that longitudinal ultrasound propagated through only six of the twenty rods (five were smooth on both ends, while one was smooth on only one end). Shear ultrasound propagated through only one rod (which was smooth on both ends). This meant that tension calculations could be made for only one of the 50 ft rods. For this rod, the tension was calculated as a load of 90,359 lb and a tensile stress of 56,251 psi. The design specifications called for a load of 86,500 lb, giving an experimental error of only 4%. It is not known why the two required modes of ultrasound propagated through only one of the rods.

Previous laboratory experiments on a failed 36 ft rod removed from another dam, showed there should have been enough signal strength (about 46 dB gain remained) to interrogate a 50 ft rod. The system was calibrated using that rod. Some signal improvements were obtained onsite by careful polishing of the rod ends. Possible explanations for the increased attenuation are that the composition of these rods is slightly different than the test rod, and that the signal was dispersing into the filler material in contact with the rods. The laboratory rod tests were performed in air.

The second field test was conducted at West Point Dam in Georgia (see Figure 2 and Figure 5). On one pier, 37 rods measuring 38 – 48 ft were tested. (One rod, ee4 by our nomenclature, was broken and therefore not tested.) The filler material was grease. Both longitudinal and shear ultrasonic signals were obtained for all rods. Results of these measurements are shown in Figure 6 as a percentage of the design-specified rod tension.

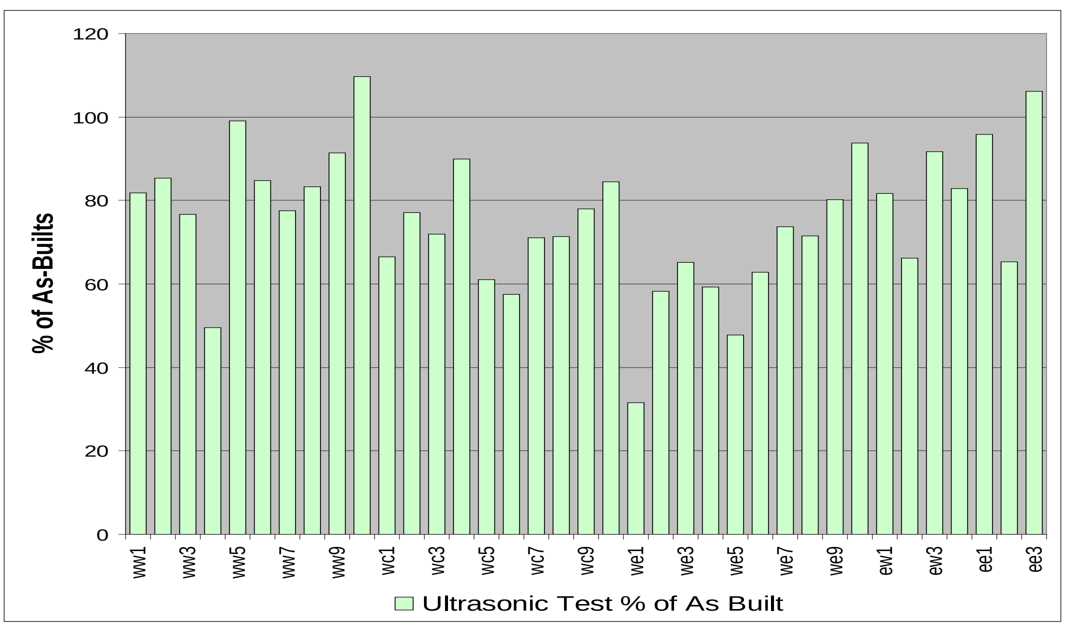


Figure 6. Measured rod tension as percentage of design specification tension for West Point Dam.

There is quite a variance in the tension measurements. The average measured value was 85,038 lb. The average as-built value is 112,543 lb. The standard deviation of the measured values is 17,839 lb, while the standard deviation of the as-built values is 2,263 lb. One would expect the rods to change tension uniformly and without such extreme variance. We have high confidence in our measurements. Unlike the Keystone (Oklahoma) test, the acoustic signals were easily detectable. The difficulties in the Oklahoma test were because of shear wave attenuation. (The attenuation of the shear wave was four to ten times greater than that of the longitudinal wave.) We were able to obtain longitudinal and shear wave measurements on all 37 tested rods, but obtaining a shear measurement was difficult for a few of the 48 ft rods. This led us to conclude that our current instrumentation and transducers are suitable for use on rods up to 45 ft.

The third field test was conducted at Kaskaskia Lock and Dam in Illinois (Figure 7). Rod ends are shown in Figure 8. Of the 112 rods in the sample, 42 measured 42 ft long, 42 were 46 ft, and 28 were 50 ft. All rods were 1.25 in. diameter, and the filler material was grout.

Figure 7. Site of third field test, Kaskaskia Lock and Dam, Illinois.

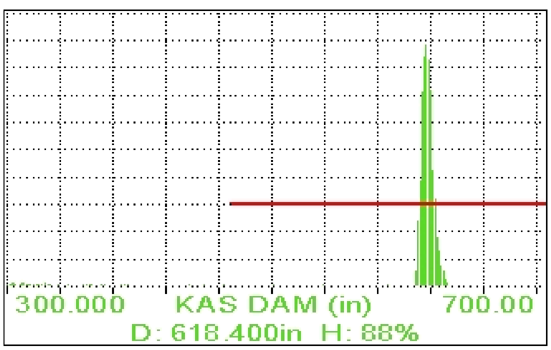
Figure 8. Rod ends at Kaskaskia Lock and Dam (left); broken rod (right).

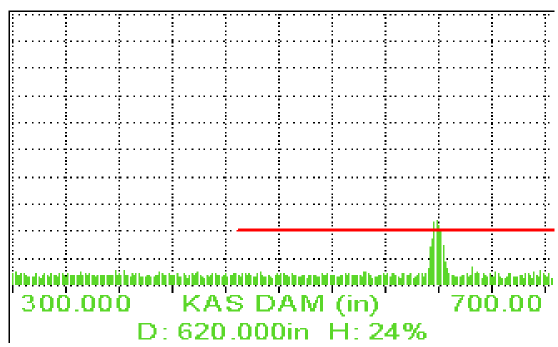
Ultrasonic data were obtained for 111 of the 112 tendon rods (rod P3W-A3 was broken). Unfortunately, the increased wave attenuation due to absorption by grout prevented shear wave measurements for all rod lengths. Tension could not be calculated due to the lack of shear wave data. However, longitudinal wave measurements indicated that no rods were broken internally. All length measurements using the longitudinal wave agreed very closely with as-built lengths. We can also infer that rod tension when the grout set has remained the same. The rods are being held firmly in place by the grout, as indicated by the broken rod that remains and cannot be extracted.

There was also a large variation of longitudinal wave attenuation among the rods. For example, a longitudinal measurement was obtained from rod P1E-D3 using a 2.25 MHz sensor driven at 400 V, which had 24% echo height using 110 dB of receiver gain. On another rod (P1E-D2, which was right next to P1E-D3), the same sensor, again driven at 400 V, gave an 88% echo height using 96 dB of receiver gain (see Figure 9).

Figure 9 and Figure 10 (next page) each illustrate both the simplicity and difficulty of making field measurements. These figures contain screen captures from the ultrasonic detector instruments during data collection at the Illinois location.

The screen capture and table on the left in both Figure 9 and Figure 10 were produced by a normal echo from a "normally" behaving 50 ft rod (P1E-D2) using a 0.75 in. diameter 2.25 MHz sensor. (This sensor was used for all longitudinal mode testing.) Receiver gain is 96 dB. Note that the height of the echo is 88% of full screen height and the bottom axis is not noisy. The red line is the gate[1], with a level of 30% of screen height. The distance the wave traveled to the end of the rod is 618.400 in. (51.5 ft).



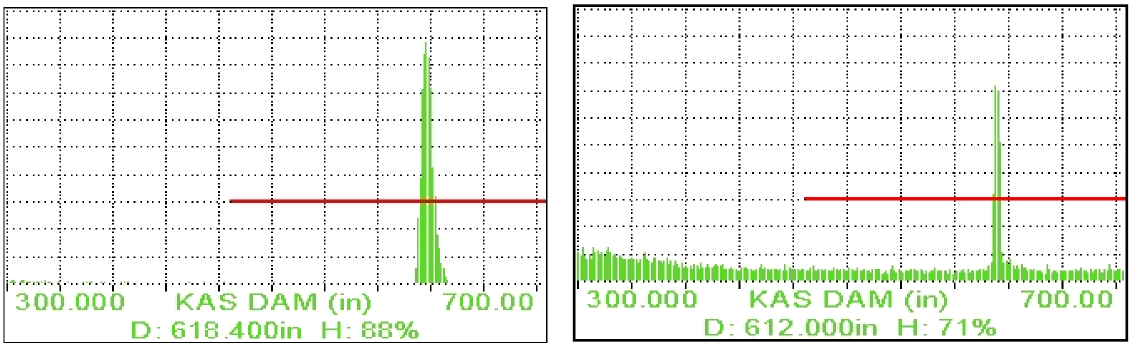


CAL	Range	Delay	Vel	Zero
	400.00	300.000	0.2307	0.000
	Gain	Ref		
	96.0	82.5		
AMP	Freq	Detect	Reject	Contour
	2.0 MHZ	Full	0	0
TX	Tx Width	Damping	Volts	PRF MAX
Single	360	400 Ohms	400v	35 Hz
GATE 1	State	Start	Width	Level
	On +Ve	466.400	384.000	30.0

CAL	Range	Delay	Vel	Zero
	400.00	300.000	0.2307	0.000
	Gain	Ref		
	110.0	82.5		
AMP	Freq	Detect	Reject	Contour
	2.0 MHZ	Full	0	0
TX	Tx Width	Damping	Volts	PRF MAX
Single	250	400 Ohms	400v	35 Hz
GATE 1	State	Start	Width	Level
	On +Ve	466.400	384.000	20.0

Figure 9. "Normal" rod with 2.25 MHz sensor (left); "abnormal" rod with 2.25 MHz sensor (right).

[1] The value of the peak must be greater than the gate level and within the distance interval for the instrument to display the distance (horizontal axis) and the amplitude (vertical axis) values of the peak.



CAL	Range	Delay	Vel	Zero
	400.00	300.000	0.2307	0.000
	Gain	Ref		
	96.0	82.5		
AMP	Freq	Detect	Reject	Contour
	2.0 MHZ	Full	0	0
TX	Tx Width	Damping	Volts	PRF MAX
Single	360	400 Ohms	400v	35 Hz
GATE 1	State	Start	Width	Level
	On +Ve	466.400	384.000	30.0

CAL	Range	Delay	Vel	Zero
	400.00	300.000	0.2307	0.000
	Gain	Ref		
	110.0	82.5		
AMP	Freq	Detect	Reject	Contour
	1.0 MHZ	Full	0	0
TX	Tx Width	Damping	Volts	PRF MAX
Single	500	400 Ohms	400v	35 Hz
GATE 1	State	Start	Width	Level
	On +Ve	466.400	384.000	30.0

Figure 10. "Normal" rod with 2.25 MHz sensor (left); "normal" rod with 1.0 MHz sensor (right).

An echo from an "abnormally" responding 50 ft rod (P1E-D3) using the standard 0.75 in. diameter 2.25 MHz sensor with a higher gain of 110 dB is shown on the right in Figure 9. The change in decibels from the normal situation is –25.3 dB, or just 5.4% the strength of the normal signal from the standard sensor on a normal rod. There is noise along the bottom axis due to the high gain. The red line is the gate level, set to 20% of screen height. The level was reduced to measure the lower echo height. The specific reason for the high ultrasonic wave attenuation in this rod is not known. However, it may indicate that a larger surface area of the rod, compared to the other rods, is in direct contact with the grout. Snell's Law predicts that a large percentage of the wave (63.4% for concrete, which has a base composition similar to grout) is refracted into the grout and absorbed due to the grout's higher attenuation coefficient. The more of the rod's surface is in direct contact with the grout, the more of the waves are refracted into the grout and absorbed, leading to the appearance of increased wave attenuation in the rod. Therefore, the attenuation in the rod is most probably directly related to the amount of grout in direct contact with the rod. The increased attenuation of the waves is another indication that the rods are firmly held in the grout.

The screen capture and table on the right of Figure 10 are from the "normally" behaving 50 ft long rod (P1E-D2) using a 1.0 in. diameter 1.0 MHz sensor. Note that a much higher gain (110 dB) compared to the 2.25 MHz sensor was required to obtain an acceptable signal; the height of the echo is 71% of full screen height; and there is noise along the bottom axis. The gate is still set at a level of 30% of screen height. The change in decibels of the peak from the normal situation is –15.9 dB[2]. This means the peak signal strength using the 1.0 MHz sensor is 0.16[3] (16%), the peak signal strength of the 2.25 MHz sensor. Ultrasonic theory says that attenuation decreas-

[2] $-15.9 = \left[96 - \left(110 + 20 \times \log_{10}\left(88/71\right)\right)\right]$

[3] $0.16 = \left[10^{-15.9/20}\right]$

es with decreasing frequency. It is unknown why, on this rod, a lower-frequency signal is attenuated more than a higher-frequency signal.

MEASUREMENT ISSUES: There are many difficulties with ultrasonically measuring the tension of anchor rods in situ. The greatest is the attenuation of the acoustic signals, especially the shear wave. Additional wave-propagation problems are reflection, refraction, beam spread, and coupling of the signal to the rod from the transducer. Unfortunately these difficulties are inherent in the physics of the problem and are very difficult to overcome. The measurement also appears to be very dependent on the medium surrounding the rod — grease or grout in the current work.

The preferred measurement method is to measure the longitudinal and shear wave velocities directly and compute the tension using the formula in Equation 1. This gives a quantitative result. Although modeling software can be used to compute the value of the shear velocity from the measured velocity of the longitudinal wave and two echoes, this is considered qualitative since the technique depends on the model used. For example, the model presented in ERDC/CHL CHETN-IX-37 (Part 1–Theory) did not take into account the medium surrounding the rod. That model would need to be redone to incorporate the results of the grouted rod tests.

SUMMARY: Field tests of a new ultrasonic tension-measurement method were conducted at three Corps of Engineers dams, located in Oklahoma, Georgia, and Illinois.

At Keystone Dam in Oklahoma, we demonstrated that the technique could measure tension in rods up to 50 ft long, and the ultrasonically measured values were within 4% of the mechanically measured values. For unknown reasons, the longitudinal wave propagated through only six of the twenty rods, and the shear wave propagated through only one rod. In retrospect, based on the results of the West Point tests, we were probably very near the measurement limit of our system.

At West Point Dam in Georgia, we obtained measurements on each of the 37 rods tested, but the quality and consistency of the signal varied. This led to wide variability in the computed rod tensions. When compared with the most recent tension measurements, made by jacking, there is quite a variance in the tension measurements. The average measured value is 85,038 lb. The average as-built value is 112,543 lb. One would expect the rods to change tension uniformly and without such an extreme variance. We have high confidence in our measurements because the acoustic signals were easily detectable. We were able to obtain longitudinal and shear wave measurements on all 37 rods, though obtaining a shear measurement was difficult for a few of the longer (48 ft) rods. This result led us to conclude that our current instrumentation and transducers are suitable for use on rods up to 45 ft.

At Kaskaskia Lock and Dam in Illinois, ultrasonic data were obtained for each of the 111 rods tested. There was a large variation of longitudinal wave attenuation among the rods. Unfortunately, as noted in the main text, the grout in the tendon conduit prevented shear wave measurements for all rods. Therefore, tension could not be calculated. However, because all length measurements using the longitudinal wave agreed very closely with as-built lengths, we can conclude that none of the 111 rods is broken. We can also infer that the tension that was in the rods when the grout set has remained the same since then.

When perfected, the benefits of this acoustic NDE tension-measurement technology will include

- rapid, noninvasive tension measurement of embedded steel rods in the field
- ease of measurement where at least one rod end is available, even where access is difficult

- cost reduction by a factor of 10 compared with the present lift-off testing method
- facilitation of more frequent testing and improved structural evaluation.

FUTURE WORK: There are several difficulties with perfecting this tension measurement method for use in the field, mostly involving the propagation of the ultrasonic waves. Further laboratory studies of wave propagation will be done using the Anchor Rod Test Bed, located at the Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS. This facility accommodates the testing of rods approximately 60 ft long under tension with several different types of conduit-filler materials.

An error analysis will be performed on the measurement and computation methods; specifically, how instrument quantization and reading errors, and possible errors in material property values, affect the tension computation.

POINTS OF CONTACT: This CHETN is a product of the Acoustic Nondestructive Testing work unit of the Navigation Systems Research Program (NavSys) being conducted at the U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory. Questions about this technical note can be addressed to Mr. Michael K. McInerney at 217-373-6759; e-mail Michael.K.Mcinerney@usace.army.mil. For information about the NavSys Research Program, contact the Program Manager, Charles E. (Eddie) Wiggins at 601-634-2471; e-mail Charles.E.Wiggins@usace.army.mil. This CHETN should be cited as follows:

> McInerney, M.K. 2013. *Acoustic Nondestructive Testing and Measurement of Tension for Steel Reinforcing Members*. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-IX-38. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

REFERENCES

Carlyle, J.M., V. Hock, M. McInerney, and S. Morefield. 2004. *Mathematical Tension / Corrosion Prediction Models for Tainter Gate Tendon Rods*. Final Report to the U.S. Army Corps of Engineers, Contract DACW42-03-P-0289. Champaign, IL: U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL).

Carlyle, J.M., V. Hock, M. McInerney, and S. Morefield. 2004. *Nondestructive Testing for Service Life Prediction of Reinforced Concrete Structures*. Final Report to the U.S. Army Corps of Engineers, Champaign, IL: U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL).

McInerney, Michael K., Sean W. Morefield, Vincent F. Hock, Victor H. Kelly, and John M. Carlyle. Device for Measuring Bulk Stress via Insonification and Method of Use Therefor. U.S. Patent Number 7,614,303 B2, issued 10 November 2009.

Engineer Manual EM 1110-2-2702. 1 January 2000. *Design of Spillway Tainter Gates*. Washington, DC: Headquarters, U.S. Army Corps of Engineers.